European Journal of Operational Research 000 (2016) 1–9

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Discrete Optimization

Integrated scheduling on a batch machine to minimize production, inventory and distribution costs

Ba-Yi Cheng[a,b], Joseph Y-T. Leung[a,b,c,*], Kai Li[a,b]

[a] School of Management, Hefei University of Technology, Hefei 230009, PR China
[b] Key Laboratory of Process Optimization and Intelligent Decision-Making, Ministry of Education, Hefei 230009, PR China
[c] Department of Computer Science, New Jersey Institute of Technology, Newark, NJ 07012, USA

ARTICLE INFO

Article history:
Received 1 March 2016
Accepted 4 September 2016
Available online xxx

Keywords:
Batch-processing machines
Production
Inventory
Distribution
Approximation algorithms

ABSTRACT

We consider the problem of scheduling a set of jobs on a single batch-processing machine. Each job has a size and a processing time. The jobs are batched together and scheduled on the batch-processing machine, provided that the total size does not exceed the machine capacity. The processing time of the batch is the longest processing time among all the jobs in the batch. There is a single vehicle to deliver the final products to the customer. If the vehicle has not returned, completed batches will be put into the inventory. In this paper, we consider the problem of minimizing the production, delivery and inventory costs. We show that if the jobs have the same size, there is an $O(n\log n)$-time algorithm to find an optimal solution. If the jobs have the same processing time, there is a fast approximation algorithm with an absolute worst-case ratio less than 1.783 and an asymptotic worst-case ratio equal to 11/9. When the jobs have arbitrary sizes and arbitrary processing times, there is a fast approximation algorithm with absolute and asymptotic worst-case ratios less than or equal to 2, respectively.

1. Introduction

Manufacturers are now facing intense competition in terms of price. In order to lower the price, each manufacturer must reduce its total cost which includes the production cost, delivery cost and inventory cost. Imagine a manufacturer receiving an order to produce certain goods for a customer. First, the products must be produced by one or more machines. After the products are produced, they must be delivered by one or more vehicles to the customer. If no vehicle is available, the completed product must be stored in a warehouse until a vehicle becomes available. Thus, there are three kinds of cost associated with this process: production cost, delivery cost and inventory cost. From the manufacturer point of view, he is interested in minimizing the total cost.

In this paper, we consider the problem of scheduling a set of jobs on a single batch-processing machine with a fixed capacity. A batch-processing machine can process several jobs together as a batch, provided that the total size of all the jobs in the batch does not exceed the capacity of the machine. Each job has a size and a processing time. The processing time of a batch is the longest processing time among all the jobs in the batch. The production cost is directly proportional to the total time taken to process all the jobs. There is a single vehicle to deliver the products to the customer. The travel time from the manufacturer to the customer is known and is fixed. The delivery cost will be proportional to the number of runs the vehicle makes. If the vehicle is not available (because it is making a delivery to the customer) when the batches are completed, the batches will be stored in a warehouse which incurs an inventory cost. Our problem is to find an integrated schedule that minimizes the total cost.

Batch-processing machines occur quite often in many industries such as semi-conductor companies, metal-working companies, porcelain companies and food-making companies. In all of these companies, the production cost is usually the highest since the processing time of a batch is usually quite long. Moreover, the production process consumes a lot of energy. The production cost is usually proportional to the total time taken to produce the products. The cost of each delivery can be calculated since we know the exact route from the manufacturer to the customer. For a given route, the delivery cost includes fuel cost, road fees and labor cost for driver and workers. The delivery cost is usually proportional to the number of deliveries, and it is much lower than the production cost. Completed batches that are not immediately delivered will be stored in a warehouse which will incur an inventory cost. The inventory cost is usually proportional to the time taken by the batches staying in the warehouse. Among the three costs,

* Corresponding author at: Department of Computer Science, New Jersey Institute of Technology, Newark, NJ 07012, USA. Fax: +1 973 596 5777.
E-mail addresses: leung@cis.njit.edu, leung5of6@gmail.com (J.Y-T. Leung).

http://dx.doi.org/10.1016/j.ejor.2016.09.009
0377-2217/

production cost is the most expensive one, followed by the delivery cost and finally followed by the inventory cost. Thus, in our schedule, we give the highest priority to the production cost, then the delivery cost and finally the inventory cost.

This type of scheduling problem integrates production cost with distribution and inventory costs. Unfortunately, even minimizing the production cost on a single batch-processing machine is intractable. Uzsoy (1994) showed that the problem of minimizing the makespan of a set of jobs with arbitrary sizes on a single batch-processing machine is strongly NP-hard. Approximation algorithms have been proposed to solve the single-machine scheduling problem (Cheng, Cai, Yang, & Hu, 2014a; Leung, Ng, & Cheng, 2008; Li, Li, Wang, & Liu, 2005; Zhang, Cai, Lee, & Wong, 2001). Tang, Meng, Chen, and Liu (2016) considered the batch scheduling problem arising in steel production and proposed a branch and price solution. They showed that benefits can be increased when the batch scheduling is done well. Giglio (2015) considered the single-machine problem with sequence-dependent batch setup and controllable processing times. Two methods are compared including a mathematical programming and optimal control strategies. Intelligent algorithms such as genetic algorithms (Peres & Monch, 2013; Zegordi, Abadi, & Nia, 2010) and simulated annealing algorithms (Melouk, Demodaran, & Chang, 2004) have also been used. Multi-machine problems have also been studied. Dosa, Tan, Tura, Yan, and Lanyi (2014) presented improved bounds for the single-machine and parallel-machine problems. The bounds are respectively 1.7 and 2. Liu, Ng, and Cheng (2009) and Jula and Leachman (2010) proposed algorithms for parallel batch-processing machines. Zhang, Cai, and Wong (2003) studied the online problem and provided an online algorithm with a competitive ratio of $\frac{\sqrt{5}+1}{2}$. Sung and Min (2001) and Cheng, Yang, Hu, and Li (2014b) considered the two-machine flowshop problem. Oulamara, Kovalyov, and Finke (2005) considered the flowshop problem with unbounded batch-processing machines and provided approximation algorithms with one, two and three batches. Current research has concentrated on scheduling problems that minimizes the production cost. Little attention has been paid to the integrated scheduling that minimizes the production and delivery costs. We note that in recent years integrated scheduling with the classical scheduling model has aroused interests of many researchers. We will briefly review these research next.

Hall and Potts (2003) considered general integrated scheduling problem for the manufacturer that includes material supplying, production, and product distribution. They demonstrated that cooperation between the supplier and manufacturer can reduce total system cost in the supply chain by at least 20%. Other researchers studied two types of integrated scheduling problems. The first type is the three-stage problem that includes the supplier, manufacturer, and customers. Selvarajah and Steiner (2009) proposed a 3/2 approximation algorithm for the problem of minimizing the delivery and inventory holding costs. Sawik (2009) extended the problem to a long-term product case. The objective is to minimize the overall cost of the supply chain, including the inventory holding, production and delivery costs. Yeung, Choi, and Cheng (2011) and Osman and Demirli (2012) considered the three-stage problem with time windows and synchronized replenishment, respectively. The three-stage problems involve three parts of the supply chain and are complex to solve. Other researchers studied the two-stage problems. However, many of them are still NP-hard (Chen & Vairaktarakis, 2005). The research on two-stage problems can be divided into two parts; i.e. the scheduling between the supplier and manufacturer and the scheduling between the manufacturer and customer. Chen and Hall (2007) investigated the conflict between the optimal schedules of the supplier and manufacturer and they proposed a cooperation mechanism for the two sides. Agnetis, Hall, and Pacciarelli (2006) proposed an interchange cost that will be incurred when the orders of the jobs are different in the optimal schedules of the two sides. They also provided a cooperation scheme. Algorithms for solving the supplier-manufacturer problem include approximation algorithms (Averbakh & Xue, 2007; Selvarajah & Steiner, 2006) and genetic algorithm (Naso, Surico, Turchaiano, & Kaymak, 2007). Two-stage problems between the manufacturer and customer have also been considered. Chen and Pundoor (2006) considered time-sensitive products and Hall and Liu (2010) considered capacity allocation. Cheng, Leung, Li, and Yang (2015) considered the two-stage scheduling problem where the manufacturer uses batch-processing machines to process jobs and deliver products to the customer. The objective is to optimize the service span, that is, the period lasting from the beginning of the production to the end of distribution. Averbakh and Baysan (2012) considered a semi-online integrated scheduling problem and proposed a semi-online algorithm with competitive ratio $\frac{2D}{D+P}$, where D is the cost of a delivery and P is the lower bound of the processing times of jobs. Little research has been done on integrated scheduling of batch-processing machines. Our paper can be viewed as a two-stage problem between the manufacturer and customer.

The rest of the paper is organized as follows. In Section 2, we give the model and some notations that will be used throughout the paper. In Section 3, we consider the special case where the jobs have identical sizes. We propose an optimal algorithm for this case. In Section 4, we consider the special case where the jobs have identical processing times. We propose a fast approximation algorithm and show that it has an absolute worst-case ratio less than 1.783 and an asymptotic worst-case ratio equal to 11/9. In Section 5, we consider the general case where the jobs have arbitrary sizes and arbitrary processing times. We provide a fast approximation algorithm with absolute and asymptotic worst-case ratios less than or equal to 2, respectively. Finally, in Section 6, we conclude the paper and present some directions for future research.

2. Model and notations

There are n jobs to be processed. The job set is $J = \{1, 2, \ldots, n\}$. Each job j has a size s_j and a processing time p_j. The manufacturer has a single batch-processing machine with a capacity of D. The batch set is $B = \{B_1, B_2, \ldots, B_z\}$, where z denotes the number of batches. The total size of all the jobs in a batch cannot exceed D. The processing of batch B_i cannot be interrupted until all the jobs in B_i are completed. Therefore, the processing time of B_i is $P_i = \max\{p_j | j \in B_i\}$. The production cost is PC given by the following equation:

$$PC = \lambda_1 \sum_{i=1}^{z} P_i, \tag{1}$$

where $\lambda_1 > 0$ is a constant. The production cost is a linear function of the production time. The products will be delivered to the customer by a single vehicle. The capacity of the vehicle is $K = rD$, where r is a positive integer. We assume that each batch is packaged in a standard-size box or pallet. Therefore, each delivery consists of an integral number of batches. The delivery set is $\{d_1, d_2, \ldots, d_x\}$ and the number of deliveries is x. The travel time of the vehicle from the manufacturer to the customer (and from the customer to the manufacturer) is T. The delivery cost DC is given by the following equation:

$$DC = \lambda_2 x, \tag{2}$$

where $\lambda_2 > 0$ is a constant. The delivery cost is a linear function of the number of deliveries. After a batch is completed, the prod-